5

Short Line Faults

5.1 General

The short line fault is so-called because the fault in this case occurs at a short distance along a transmission line from the circuit breaker. The distance of interest is in the order of hundreds of meters to a kilometer or so and the fault is sometimes referred to as a kilometric fault.

The circuit for this case is shown in Figure 5.1 where V_S is the source voltage peak line to ground voltage, X_S the source impedance, V_L the peak voltage at the circuit breaker line side terminal at current interruption and X_{eff} and Z_{eff} are the effective line and surge impedances, respectively. The fault current I_L is usually expressed as a percentage of the circuit breaker short circuit current rating I_S. A 90% short line fault thus means that $I_L = 0.9I_S$.

The circuit breaker transient recovery voltage (TRV) is the difference between the source side TRV and the line side transient. At current interruption the voltage on the line side is V_L with a decreasing linear voltage profile to zero along the line to the fault location as shown in Figure 5.2. The line side voltage must go to zero but it does not ring down in the way of an oscillatory circuit because now we are dealing with distributed rather than the lumped elements discussed earlier in Chapters 2 and 4. Instead the line voltage goes to zero by means of successive traveling waves as shown in the next section.

5.2 Line Side Voltage Calculation

The initial condition for the line side voltage is as shown in Figure 5.2. Calculation of the line side voltage is done by considering two steady-state waves each at half the initial voltage and traveling in opposite directions (Figure 5.2). The progression of the right-going wave is shown in Figure 5.3 in time steps of one-quarter of the line traveling time. Likewise, the progression of the left-going wave is shown in Figure 5.4 in the same time steps. This wave is immediately totally reflected at the open circuit breaker and essentially follows the right-going with a reversed profile. The voltage profile on the line at any point in time is determined by summing the individual wave voltages as shown in Figure 5.5. The voltage at the fault location must always sum to zero.

After twice the line travel time t_L, the two waves have returned to the circuit breaker with reversed polarity as shown in Figure 5.5. The process starts over again and the two waves

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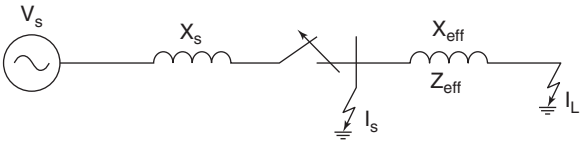


Figure 5.1 Short line fault circuit representation.

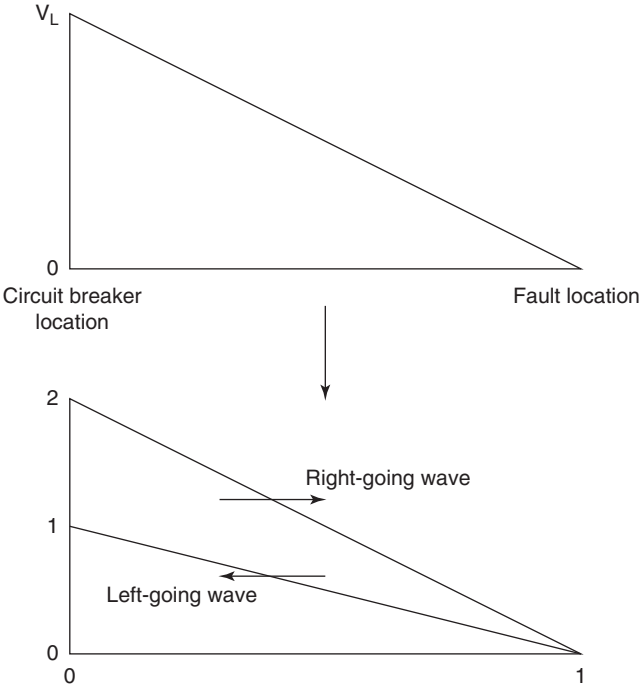


Figure 5.2 Short line fault traveling wave analysis approach.

will return after the same time interval with positive polarity. If we take the voltage at the circuit breaker at each instant in time and plot it against travel time, the voltage has the sawtooth type waveshape shown in Figure 5.6. Viewed in oscillatory circuit terms, the starting point of the transient is V_L, the axis of oscillation is zero and the peak value is $2V_L$. This, of course, assumes no damping or other considerations and the actual peak is given by kV_L where k is a so-called peak factor, in effect another quasi-amplitude factor.

With reference to Figure 5.1, we can write:

$$\begin{aligned} V_L &= V_S - X_S I_L \\ &= V_S - \frac{V_S}{I_S} I_L \\ &= V_S\left(1 - \frac{I_L}{I_S}\right) \\ &= V_S(1-M) \text{ where } M \text{ is} \frac{I_L}{I_S}. \end{aligned}$$

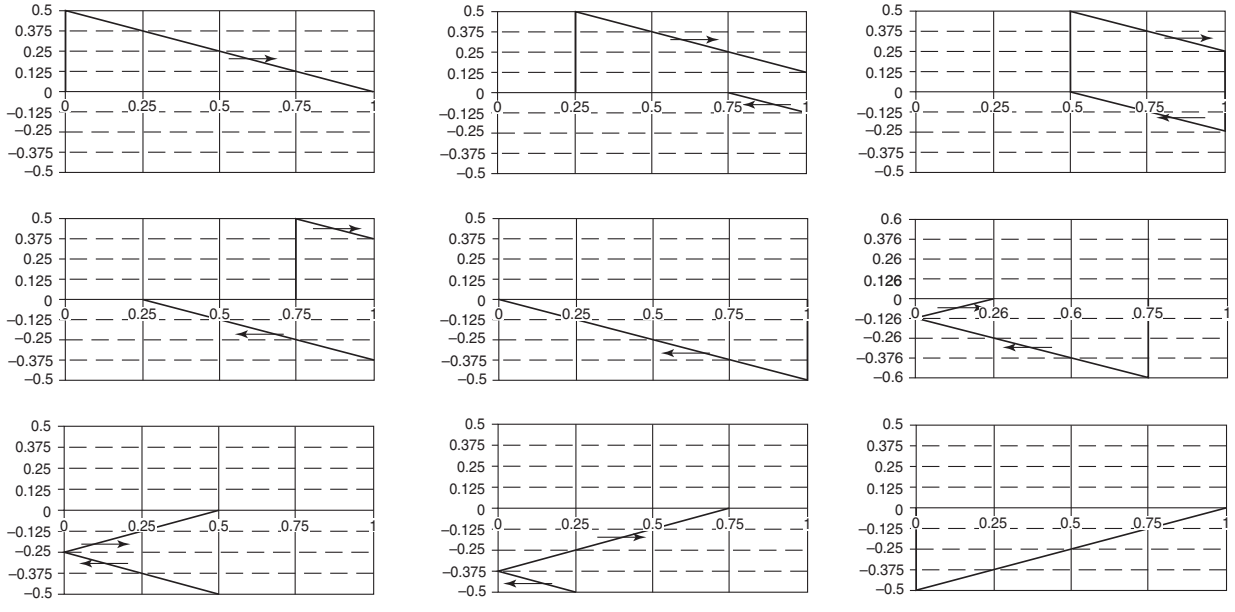


Figure 5.3 Short line fault right-going traveling wave.

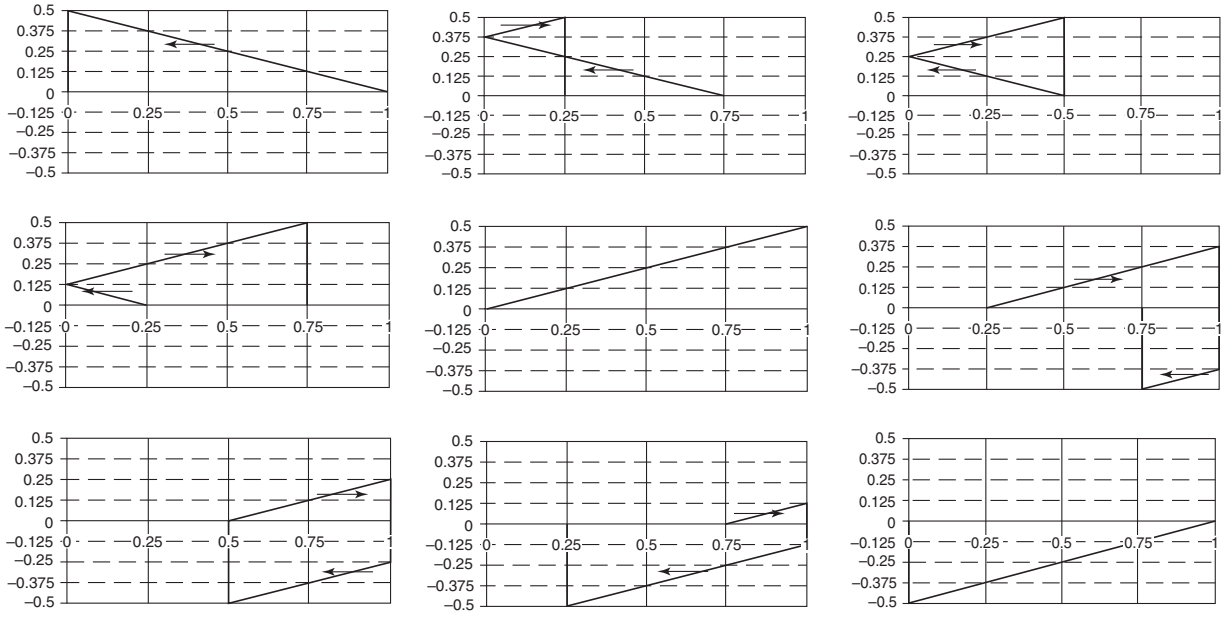


Figure 5.4 Short line fault left-going traveling wave.

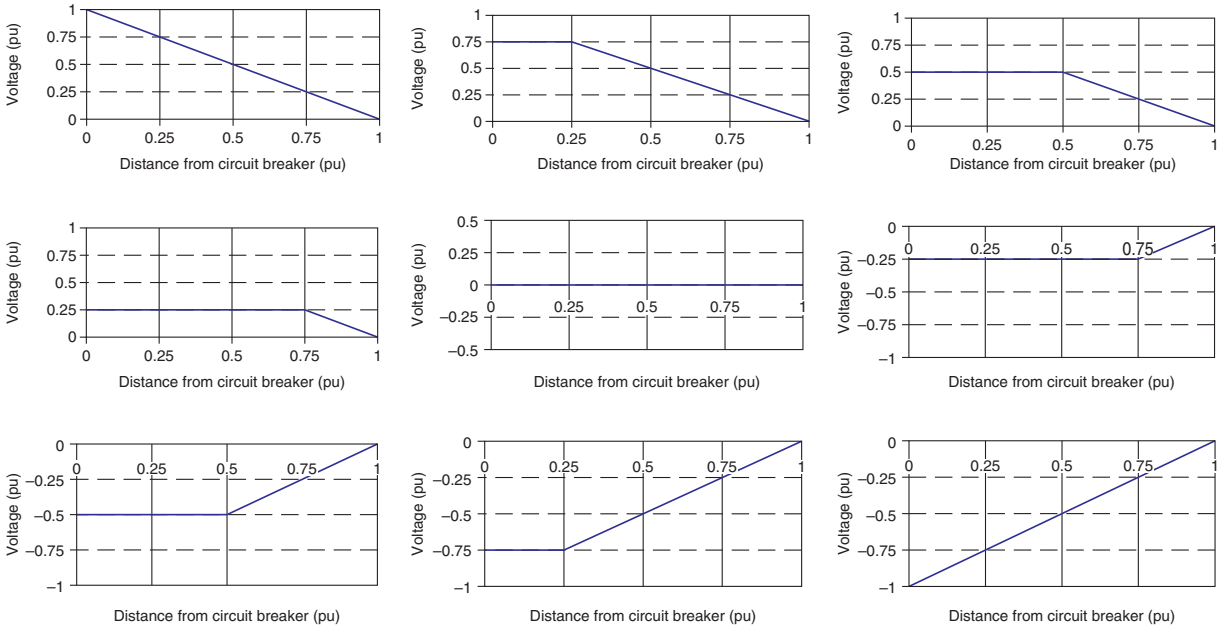


Figure 5.5 Voltage profile on the line versus travel time.

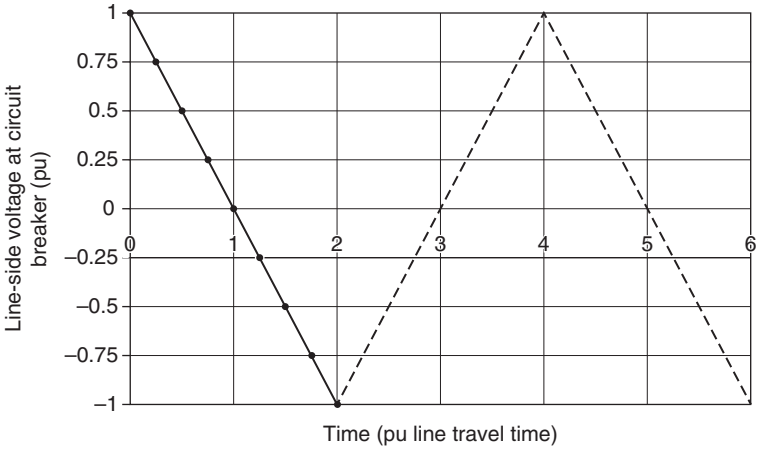


Figure 5.6 Voltage at circuit breaker as function of travel time.

The peak value of the line side transient V_{pk} is:

$$V_{pk} = k(1-M)\,V_S. \tag{5.1}$$

The rate of rise of restriking voltage (RRRV) of the line side transient is given by:

$$\begin{aligned} \text{RRRV} &= \frac{V_{pk}}{2t_L} \\ &= Z_{eff}\frac{di}{dt} \\ &= \sqrt{2}\omega I_L Z_{eff}. \end{aligned} \tag{5.2}$$

To now calculate the value of k, the reader can readily verify that the sequence network for a single line to ground fault is as shown in Figure 5.7. The sequence impedances are in series and Z_{eff} is given by:

$$\begin{aligned} Z_{eff} &= \frac{Z_1 + Z_2 + Z_0}{3} \\ &= \frac{2Z_1 + Z_0}{3} \text{ for } Z_1 = Z_2. \end{aligned}$$

Likewise, ignoring resistance and considering only reactance and thereby inductance both per unit length of line, we can write:

$$L_{eff} = \frac{2L_1 + L_0}{3}.$$

From Eq. (5.2):

$$V_{pk} = 2t_L\sqrt{2}\omega I_L\left(\frac{2Z_1 + Z_0}{3}\right)$$

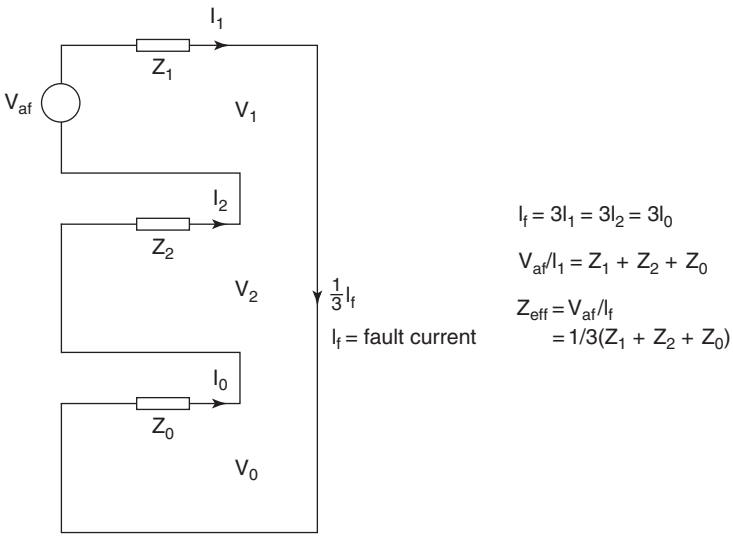


Figure 5.7 Sequence network for a single line to ground fault.

and V_L is given by

$$V_L = \sqrt{2} I_L \omega \left(\frac{2L_1 + L_0}{3} \right) l$$

where l is the distance to the fault. Taking v as the velocity of the traveling wave, k is calculated as follows:

$$\begin{aligned} k &= \frac{V_{pk}}{V_L} \\ &= 2\frac{t_L}{l}\left(\frac{2Z_1 + Z_0}{2L_1 + L_0}\right) \\ &= \frac{2}{v}\left(\frac{2Z_1 + Z_0}{2L_1 + L_0}\right) \\ &= \frac{2}{v}\frac{Z_1(2 + Z_0/Z_1)}{L_1(2 + L_0/L_1)}. \end{aligned} \tag{5.3}$$

Now we will make the assumption that the high frequency and power frequency per unit length inductances (L_1) and capacitances (C_1) of the line are approximately equal.

$$Z_1 = \sqrt{\frac{L_1}{C_1}}$$

and

$$v = \frac{1}{\sqrt{L_1 C_1}}$$

giving $Z_1/L_1 = v$ and Eq. (5.3) becomes

$$k = \frac{2(2 + Z_0/Z_1)}{2 + L_0/L_1}.$$

Taking $L_0/L_1 = 3$ and $Z_0/Z_1 = 2$, both conservative values, $d = 1.6$ and Eq. (5.1) becomes:

$$V_{pk} = 1.6(1-M)\, V_S. \tag{5.4}$$

To illustrate the use of Eqs. (5.2) and (5.4), we will take the case of a 245 kV, 40 kA circuit breaker at 50 Hz and consider 90, 75, and 60% faults. In the IEC circuit breaker standard, these test duties are designed as L90, L75, and L60, respectively. Also, the standard specifies that $Z_{eff} = 450$ ohm.

For L90, we can write:

$$\text{RRRV} = \sqrt{2} \times 314 \times 36 \times 450 \times 10^{-6}\ \text{kV/μs}$$

$$= 7.2\ \text{kV/μs}$$

$$V_{pk} = 1.6 \times 0.1 \times \frac{245\sqrt{2}}{\sqrt{3}}\text{kV}$$

$$= 32\ \text{kV}.$$

$$\text{Time to peak } t_p = \frac{32}{7.2}$$

$$= 4.44\ \text{μs}.$$

$$\text{Distance to the fault } l = 300 \cdot \frac{t_p}{2}$$

$$= 666\ \text{m}$$

where 300 m/μs is the speed of light.

The values for all of the above cases are given in Table 5.1 and plotted in Figure 5.8.

A second case to consider is for a 245 kV circuit breaker at 50 Hz and varying short-circuit current ratings of 31.5 kA, 40kA, and 50 kA. The case results are given in Table 5.2 and plotted in Figure 5.9.

Table 5.1 L90, L75, and L60 line side transient characteristics for 245 kV, 40 kA, 50 Hz circuit breaker.

Test duty	V_{pk} kV	RRRV kV/μs	Time to peak μs	Distance to fault m
L90	32	7.2	4.44	666
L75	80	6	13.33	2000
L60	128	4.8	26.67	4000

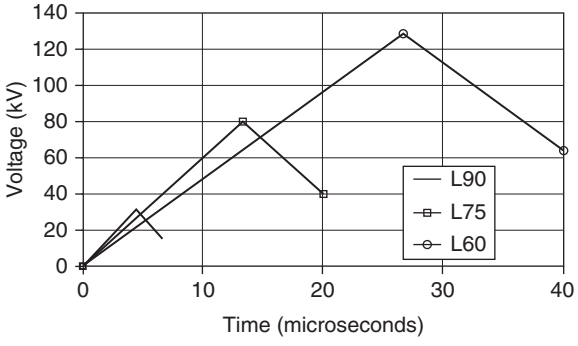
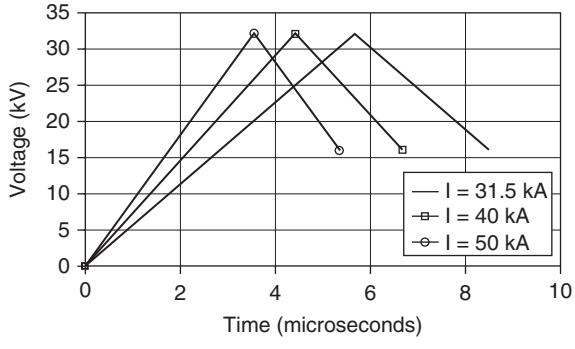


Figure 5.8 L90, L75, and L60 line side transients for 245 kV, 40 kA, 50 Hz circuit breaker.

Table 5.2 L90 line side transient characteristics for 245 kV, 50 Hz circuit breakers rated at 31.5 kA, 40 kA and 50 kA.

Short-circuit current rating kA	V_{pk} kV	RRRV kV/μs	Time to peak μs	Distance to fault m
31.5	32	5.66	5.65	847
40	32	7.2	4.44	666
50	32	9	3.55	533

Figure 5.9 L90 line side transients for 245 kV, 50 Hz circuit breakers rated at 31.5, 40, and 50 kA.



5.3 Effect of Added Capacitance

The effect of adding extra capacitance line to earth on the line side of the circuit breaker is to reduce the rate of rise of the line side transient. The peak value of the transient is unaffected since it relates only to the source voltage and the fault current (refer to Eq. (5.4)).

The effect of add capacitance C_{add} can be estimated by treating the line side transient as an undamped oscillation based on the line inductance L and an equivalent capacitance C_{eq}.

With reference to Figure 5.6 and ignoring damping, i.e. $V_{pk} = 2V_L$, the time to peak t_p is given by:

$$t_p = \pi\sqrt{LC_{eq}}. \tag{5.5}$$

t_p is also given by:

$$\begin{aligned} t_p &= \frac{V_{pk}}{\text{RRRV}} \\ &= \frac{2\sqrt{2}\omega IL}{\sqrt{2}\omega IZ_{eff}} \\ &= 2L\sqrt{\frac{C_L}{L}} \\ &= 2\sqrt{LC_L} \end{aligned} \tag{5.6}$$

where C_L is the total line capacitance.

Equating Eqs.(5.5) and (5.6) and solving for C_{eq}:

$$\begin{aligned} C_{eq} &= \frac{4}{\pi^2}C_L \\ &= 0.4C_L. \end{aligned}$$

The time to peak for the base no added capacitance case is:

$$t_{pb} = \pi\sqrt{0.4LC_L}$$

and for the added capacitance case

$$t_{pa} = \pi\sqrt{L(0.4C_L + C_{\text{add}})}.$$

The reduction in the rate of rise of the line side transient due to added capacitance is the ratio of:

$$\begin{aligned} t_{pb}/t_{pa} &= \sqrt{\frac{0.4C_L}{0.4C_L + C_{\text{add}}}} \\ &= \sqrt{\frac{C_L}{C_L + 2.5C_{\text{add}}}}. \end{aligned}$$

Equation (5.2) can now be used to derive the equation for the rate of rise with added capacitance giving:

$$\text{RRRV} = \sqrt{2}\omega IZ_{eff}\sqrt{\frac{C_L}{C_L + 2.5C_{\text{add}}}}.$$

Taking the same 245 kV, 40 kA, 50 Hz circuit breaker, we will calculate the effect of added capacitance for the L90 case. The base case with no added capacitance thus has $V_{pk} = 32$ kV and RRRV = 7.2 kV/μs. To calculate the value for C_L, the line impedance X_L is given by:

$$\begin{aligned} X_L &= \frac{V_{pk}}{1.6\sqrt{2}I} \\ &= 0.393\,\Omega. \end{aligned}$$

Alternatively:

$$X_L = \frac{245}{36\sqrt{3}} - \frac{245}{40\sqrt{3}}$$
$$= 3.929 - 3.536$$
$$= 0.393\,\Omega$$
$$L = 1.25\,\text{mH}$$
$$\text{C}_\text{L} = \frac{1.25 \times 10^{-3}}{450^2}$$
$$= 6.17\,\text{nF}.$$

For $C_{\text{add}} = 1$ nF:

$$\text{RRRV} = 7.2\sqrt{\frac{6.17}{6.17 + 2.5}}$$
$$= 6\,\text{kV}/\mu\text{s}.$$

In Table 5.3, the RRRV values are given for added capacitances of 1, 2, 5, and 10 nF and plotted in Figure. 5.10.

Table 5.3 L90 line side transient characteristics for 245 kV, 40 kA, 50 Hz circuit breaker with varying added line to earth capacitance.

C_{add} nF	V_{pk} kV	RRRV kV/μs	Time to peak μs
0	32	7.2	4.44
1	32	6.07	5.27
2	32	5.35	5.98
5	32	4.14	7.73
10	32	3.2	9.98

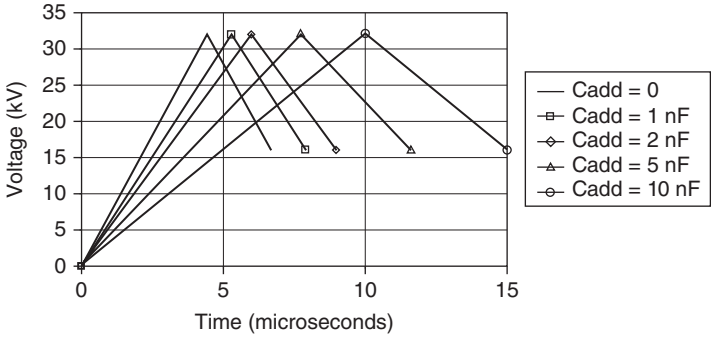


Figure 5.10 L90 line side transients for 245 kV, 40 kA, 50 Hz circuit breaker with varying added line to earth capacitance.

Applying dedicated capacitor units for the purpose of influencing the line side transient is not normal utility practice. However, there have been incidents where such capacitors were added following the failure of a circuit breaker to clear a short line fault. For maximum effect, the capacitors have to be placed as closely as possible to the circuit breaker.

5.4 Discussion

The short line fault case is characterized by a fast-rising line side transient. The case is particularly onerous for circuit breakers subject to thermal reignitions.

The short line case is treated as a single phase to earth fault event in the standards. The reason for this is that the RRRV is higher for the third-pole-to-clear than for the first-pole-to-clear. From Section 3.5 and Figure 3.21, the circuit representation for the first and third pole clearing is shown in Figure 5.11. Using current injection, the effective surge impedance for the first-pole-to-clear Z_{eff1} is given by:

$$Z_{eff1} = \frac{3Z_0Z_1}{Z_1 + 2Z_0}$$

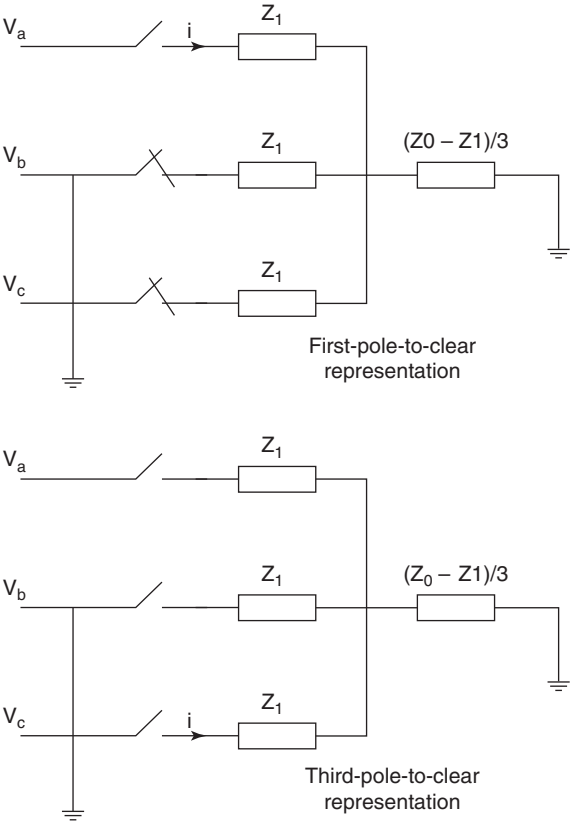


Figure 5.11 Circuit representations for first and third pole short line fault current interruption.

and for the third-pole-to-clear Z_{eff3} by

$$Z_{eff3} = \frac{2Z_1 + Z_0}{3}.$$

In general, $Z_0 > Z_1$ and the ratio of Z_0/Z_1 is such that $Z_{eff3} > Z_{eff1}$.

The test fault levels are in the T100 to T60 range and the source side TRVs are those for the terminal faults but with $k_{pp} = 1$. Note also, that the rise time of the line side transients falls within the time-delay period of the source side TRV and its contribution to the total voltage across the circuit breaker is minimal to insignificant.

Further Reading

IEC 62271-306 (2018). High-voltage switchgear and controlgear - Part 306: Guide to IEC 62271-100, IEC 62271-1 and other IEC standards related to alternating-current circuit-breakers.

IEEE C37.011 (1994). IEEE Application Guide for Transient Recovery Voltages for AC High-Voltage Circuit Breakers.

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